

# CONSTRAINING THE ORIGIN OF BASALTIC VOLCANIC ROCKS OBSERVED BY OPPORTUNITY

ALONG THE RIM OF ENDEAVOUR CRATER M. C. Bouchard<sup>1</sup>, B. L. Jolliff<sup>1</sup>, W. H. Farrand<sup>2</sup>, and D. W. Mittlefehldt<sup>3</sup> <sup>1</sup>Dept. of Earth & Planetary Sciences, Washington University, St. Louis, MO 63130 (mcbouchard@wustl.edu) <sup>2</sup>Space Science Institute, 4750 Walnut St., #205, Boulder, CO 80301, <sup>3</sup>NASA/JSC, Houston, TX, USA.

**Introduction:** The Mars Exploration Rover (MER) *Opportunity* continues its exploration along the rim of Endeavour Crater [1]. While the primary focus for investigation has been to seek evidence of aqueous alteration, *Opportunity* has observed a variety of rock types, including some that are hard and relatively unaltered [2-3]. These rocks tend to occur most commonly as “float rocks” or “erratics” where the geologic setting does not clearly reveal their origin. Along the rim of Endeavour crater (Fig. 1), such rocks, commonly noted in Panoramic Camera (Pancam) left eye composites as “blue rocks” [4], are abundant components of some of the Endeavour crater rim deposits, scree slopes, and colluvium deposits. In this abstract, we examine the similarity of several of these rocks analyzed using *Opportunity*’s Alpha Particle X-Ray Spectrometer (APXS), images and color from the Pancam, and textures observed with the Microscopic Imager (MI) [5]. At issue is the blue rocks origin; are they impact melt or volcanic, what is their age relative to Endeavour crater, and how they are related to each other?

**Occurrence of the “Blue Rocks”:** *Opportunity* encountered a few blue rocks during its traverse across Meridiani Planum. In most cases, these rocks appear to be erratics of uncertain origin such as Marquette Island (sols 2070-2120) [6], possibly a basalt. On the rim of Endeavour crater, Shoemaker breccias contain prominent blue rock clasts that are notably harder and more resistant than matrix, such as “Sarcobatus clast” (sols 3675-3676) [7].

Upon *Opportunity*’s arrival at the ridge overlooking the entrance to Marathon Valley, the blue rocks became a prominent component of the surface debris (Fig. 1), forming cobble- to boulder-sized rocks. On sol 3953, a rock informally named Sergeant Charles Floyd (SCF) (Fig. 2a) was brushed with the Rock Abrasion Tool (RAT), imaged with the MI, and analyzed with the APXS. In a nearby location, within a 25 by 35 m ovoid feature (Spirit of St. Louis), there is a prominent outcrop (“Lindbergh Mound”) composed of blue rock (Fig. 1, inset). On sol 4009, a boulder from this mound named “Roosevelt Field” (RF) was analyzed, unbrushed, with the MI and APXS (Fig. 2b). These rocks provide much of the compositional information about the blue rocks considered in this abstract.

Further inside Endeavour along the rim, cobble- to boulder-sized blue rocks are seen as dense concentrations in lag deposits (e.g., Fig. 2c). These deposits appear to be colluvium from the erosion and collapse of the interior of the Endeavour crater rim [8].

**Results:** The main results presented here are based on comparison of APXS data (<https://pds.nasa.gov/>) coupled with Pancam and MI images. For APXS data, we use a hierarchical cluster analysis (Fig. 3) and an error-weighted similarity index (SI) to compare specific compositions [9]. In addition to the aforementioned rocks, we include in this analysis other relevant compositions, some of average rock formation compositions analyzed by *Opportunity*, some from Spirit in Gusev crater, and a martian meteorite, NWA 7475/7034. In this comparison, we include mainly rock targets brushed with the RAT, but also some “clean” unbrushed targets, recognizing that some unbrushed surfaces are altered compared to rock interiors.

A first-order result is that the composition of SCF is most similar to the basaltic erratic Marquette Island, comparing brushed surfaces (Islington Bay and Peck Bay), and to the martian meteorite NWA 7475/7034 [10]. The SI values indicate strong similarity (SI: 76-229). SCF has an Mg# [molar MgO/(FeO<sub>T</sub>+MgO)\*100] of 55-59. This hard rock has an aphanitic texture with no primary lineation or fabric observable by MI.

Roosevelt Field (RF) is texturally similar to SCF but is compositionally most similar to another blue rock target “Margaret” on Wdowiak Ridge rock “Lipscomb” [11]. These two rocks have Mg# of 41-44.

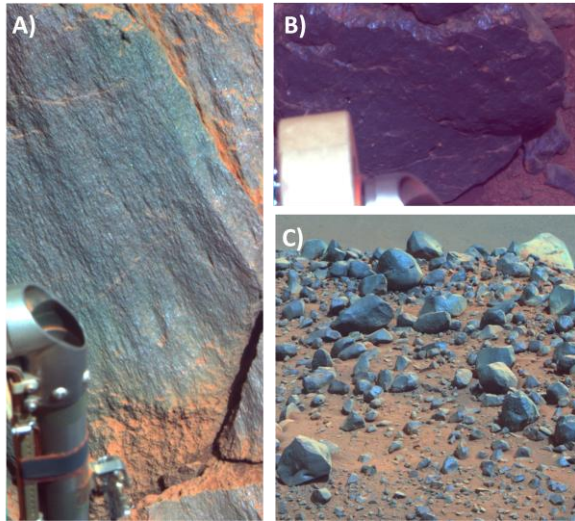
**Discussion:** Hypotheses for the origins of the blue rocks include: 1) pre-Endeavour primary basalt (i.e., Endeavour target rocks), 2) post-Endeavour primary basalt, 3) pre-Endeavour sedimentary rocks of basaltic origin, or 4) impact melt, either predating or formed by the Endeavour crater impact.

We first consider the impact-melt and sedimentary



**Figure 1.** HiRISE image with *Opportunity*’s traverse marked in yellow. Several blue rock targets and sol numbers are labelled. The inset is a Pancam mosaic of Spirit of St. Louis, PIA19394, showing locations of Lindbergh Mound and Roosevelt Field. (NASA/JPL-Caltech/Cornell/ASU).

hypotheses. If the blue rocks were impact melt, one might expect their compositions to be more like the average Shoemaker formation composition. Instead, the compositions are more endmember-like and differ from average Shoemaker breccia (Fig. 3). Texturally, the blue rocks are clast-free, hard, and aphanitic. They are resistant to weathering and break like rocks that have a homogeneous texture. They are not layered and exhibit little or no vesicularity. The lack of any sedimentary texture and the hard, resistant character lead us to reject sedimentary and impact origin hypotheses.



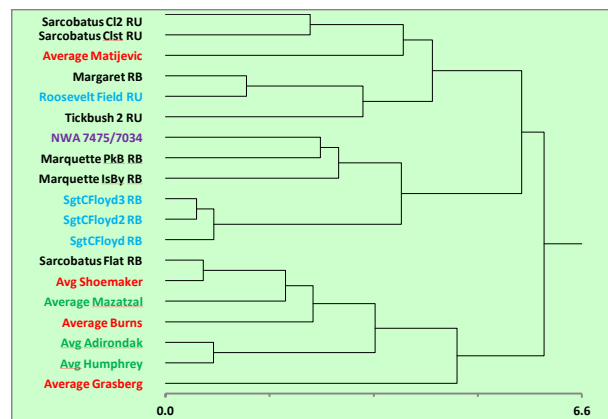
**Figure 2.** Pancam Images of “blue rocks” (Sgt. Charles Floyd, sol 3948 P2509, Roosevelt Field, sol 4011, P2550 and a coarse lag deposit of blue rocks (Sol 4484, P2552, Plymouth\_II). False-color combination of filters L257 (753, 535 and 432 nm) [12-13].

Silica and alkali contents of the blue rocks place them in the basalt field using the total-alkali-silica (TAS) classification. Pancam spectra (and Mössbauer spectra for Marquette) also suggest basaltic mineralogy [6]. Marquette and SCF are more olivine normative than RF and Margaret (which are more pyroxene rich), consistent with Mg# and suggesting a possible petrogenetic relationship such that RF and Margaret are more chemically evolved than SCF and Marquette. However, Marquette, as observed in its RAT-grind composition, is relatively enriched in MgO, and in all measurements, Cr<sub>2</sub>O<sub>3</sub>, compared to SCF. This difference and the distance between the two targets suggests that although similar in RB compositions, the two rocks may originate from different sources.

The blue rocks also cluster with an average Matijevec formation composition. By their SI values, the blue rocks are highly-to-moderately similar to the average Matijevec formation (SI: 167-644), but only moderately similar to very dissimilar to average Shoemaker formation (SI: 314-1387). Gusev basalts [14] also range from moderately similar to very dissimilar compared to the blue rocks (SI: 357-1808).

The abundance of blue rocks on the rim of Endeavour crater such as SCF, the concentration of boulders on the interior of the Endeavour crater rim, especially in the vicinity of Marathon Valley and south, and the incorporation of blue rock clasts in Shoemaker breccia could be interpreted to mean that these were target rocks when Endeavour formed. Alternatively, if as appears to be the case for RF at Lindbergh Mound, the volcanic rocks formed after Endeavour, then those present as float or in colluvium could be remnants of thin flows following degradation of Endeavour’s rim.

**Conclusion:** The endmember igneous compositions, grouping with outlier basaltic erratics, and aphanitic textures of the measured blue rocks point to a primary volcanic origin. Disparate evidence seems to support some of the basalts predating and others post-dating the Endeavour impact. Further observations may provide additional clarity.



**Figure 3.** Hierarchical cluster analysis dendrogram illustrating compositional relationships for selected rock targets, bulk averages of major Endeavour rim rock formations (red), and bulk averages of basalts at Gusev crater (green). This cluster was created using oxide weight percentages normalized on an SO<sub>3</sub>- and Cl-free basis [15]. The relationships shown demonstrate the high similarity between the Sergeant Charles Floyd, Marquette Island, and Matijevec formation rock targets. Roosevelt Field is not highly similar to Sergeant Charles Floyd and clusters loosely with other rocks measured on *Opportunity*’s traverse.

**Acknowledgements:** We thank NASA for support of the MER mission, and the MER Operations Team for the great ongoing exploration adventure.

**References:** [1] Arvidson R., et al. (2017) *LPSC* **48**, this conf. [2] Arvidson R., et al. (2014) *Science*, **343**, 441-448. [3] Squyres S., et al. (2012) *Science*, **336**, 570-576. [4] Farrand W., et al. (2016) *LPSC* 47 #2385. [5] Squyres S., et al. (2003) *J. Geophys. Res.* **108**, E12, 8062. [6] Mittlefehldt D., (2010) *LPSC*, 41, #2109. [7] Arvidson R., et al. (2016) *Am. Min.* **101**, 1389-1405. [8] Crumpler L., et al. (2017) *LPSC*, **48**, this conf. [9] Bouchard M., and Jolliff B., (2016) *LPSC* 47 #2551 [10] Wittmann A., et al. (2015) *Meteoritics & Planetary Science*, **50**, 326-352 [11] Mittlefehldt D., et al. (2015) *LPSC* 45, #2705. [12] Bell J., et al. (2003) *J. Geophys. Res.*, **108**, E12. [13] Bell J., et al. (2006) *J. Geophys. Res.*, **111**, E02. [14] McSween H., et al. (2004) *Science*, **305**, 842-845. [15] Gellert R, et al. (2006) *J. Geophys. Res.*, **111**, E02S05